On nature of scalar $a_0(980)$ and $f_0(980)$-mesons

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It is presented a critical consideration of all unusual properties of the scalar $a_0(980)$ and $f_0(980)$-mesons in the four-quark, two-quark and molecular models. The arguments are adduced that the four-quark model is more preferable. It is discussed the complex of experiments that could finally resolve this issue.

1. Introduction

Spherical Neutral Detector (SND) from the e^+e^--collider VEPP-2M in Novosibirsk has discovered [1,2] the electric dipole decays $\phi \to \gamma\pi^0\pi^0$ and $\phi \to \gamma\pi^0\eta$ in the region of the soft by strong interaction standard photons with the energy $\omega < 120\,\mathrm{MeV}$, i.e. in the region of the scalar $a_0(980)$ and $f_0(980)$-mesons $m_{\pi^0\pi^0} > 900\,\mathrm{MeV}$ and $m_{\pi^0\eta} > 900\,\mathrm{MeV}$, $\phi \to \gamma f_0(980) \to \gamma\pi^0\pi^0$ and $\phi \to \gamma a_0(980) \to \gamma\pi^0\eta$. The data are

$$\begin{aligned}
&B(\phi \to \gamma\pi^0\pi^0\,;\, m_{\pi^0\pi^0} > 900\,\mathrm{MeV}) = (0.5 \pm 0.06 \pm 0.06)\cdot 10^{-4} \\
&\text{at total}\;\; B(\phi \to \gamma\pi^0\pi^0) = (1.14 \pm 0.10 \pm 0.12)\cdot 10^{-4}\,, \qquad (1)\\
&B(\phi \to \gamma\pi^0\eta\,;\, m_{\pi^0\eta} > 900\,\mathrm{MeV}) \simeq 0.5\cdot 10^{-4}\,, \\
&\text{at total}\;\; B(\phi \to \gamma\pi^0\eta) = (0.83 \pm 023)\cdot 10^{-4}\,. \qquad (2)
\end{aligned}$$

Cryogenic Magnetic Detector-2 (CMD-2) from the e^+e^--collider VEPP-2M in Novosibirsk has confirmed both of these results [3].

The branching ratios in Eqs. (1) and (2) are great for this photon energy region and, probably, can be understood only if four-quark resonances are produced [4,5]. Note that the $a_0(980)$ meson is produced in the ϕ radiative decay as intensively as the containing strange quarks η' meson.

2. Evidences for strange quarks in the $f_0(980)$ and $a_0(980)$-mesons

To feel why numbers in Eqs. (1) and (2) are great, one can adduce the rough estimate. Let there be structural radiation without a resonance in the final state with the spectrum

$$\frac{d\Gamma(\phi \to \gamma\pi^0\pi^0(\eta))}{d\omega} \sim \frac{\alpha}{\pi}\cdot\delta_{OZI}\cdot\frac{1}{m_\phi^3}\omega^3\,,$$

where $\delta_{OZI} \sim 10^{-2}$ is a factor describing the suppression by Okubo-Zweig-Iizuka (OZI) rule. Then one gets

$$\Gamma(\phi \to \gamma\pi^0\pi^0(\eta)) \sim \frac{1}{4}\cdot\frac{\alpha}{\pi}\cdot\delta_{OZI}\cdot\frac{\omega_0^4}{m_\phi^3} \simeq 10^{-6}\,\mathrm{MeV}\,,$$

$$B(\phi \to \gamma\pi^0\pi^0(\eta)) \sim 2\cdot 10^{-7}\,, \quad \text{for} \quad \omega_0 = 120\,\mathrm{MeV}.$$

2.1. Evidences for strange quarks in the $a_0(980)$-meson

To understand, why Eq. (2) points to four-quark model, is particular easy. Really, the ϕ-meson is the isoscalar practically pure $s\bar{s}$-state, that decays to the isovector hadron state $\pi^0\eta$ and the isovector photon. The isovector photon originates from the ρ-meson, $\phi \to \rho a_0(980) \to \gamma\pi^0\eta$, the structure of which in this energy region is familiar

$$\rho \approx (u\bar{u} - d\bar{d})/\sqrt{2}\,. \tag{3}$$

The general structure of the $a_0(980)$-meson , from which the $\pi^0\eta$-system originates, is

$$a_0(980) = c_1(u\bar{u} - d\bar{d})/\sqrt{2} + c_2 s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2} + \ldots\,. \tag{4}$$

The strange quarks, with the first term in Eq. (4) taken as dominant, are absent in the intermediate state. So, we would have the suppressed by OZI-rule decay with $B(\phi \to \gamma a_0(980) \to \gamma\pi^0\eta) \sim 10^{-6}$ owing to the real part of the decay amplitude [5]. The imaginary part of the decay amplitude, resulted from the K^+K^-- intermediate state ($\phi \to \gamma K^+K^- \to \gamma a_0(980) \to \gamma\pi^0\eta$), violates the OZI-rule and increases the branching ratio [4,5] up to 10^{-5}.

The four-quark hypothesis is supported also by the J/ψ-decays. Really, [6]

$$B(J/\psi \to a_2(1320)\rho) = (109 \pm 22)\cdot 10^{-4}\,, \tag{5}$$

while [7]

$$B(J/\psi \to a_0(980)\rho) < 4.4\cdot 10^{-4}\,. \tag{6}$$

The suppression

$$B(J/\psi \to a_0(980)\rho)/B(J/\psi \to a_2(1320)\rho) < 0.04 \pm 0.008 \tag{7}$$

seems strange, if one considers the $a_2(1320)$ and $a_0(980)$-states as the tensor and scalar two-quark states from the same P-wave multiplet with the quark structure

$$a_0^0 = (u\bar{u} - d\bar{d})/\sqrt{2}\ \ ,\ \ a_0^+ = u\bar{d}\ \ ,\ \ a_0^- = d\bar{u}\,. \tag{8}$$

While the four-quark nature of the $a_0(980)$-meson with the symbolic quark structure

$$a_0^0 = s\bar{s}(u\bar{u} - d\bar{d})/\sqrt{2}\ \ ,\ \ a_0^+ = s\bar{s}u\bar{d}\ \ ,\ \ a_0^- = s\bar{s}d\bar{u} \tag{9}$$

is not cntrary to the suppression in Eq. (7).

Besides, it was predicted in [8] that the production vigor of the $a_0(980)$-meson, with it taken as the four-quark state from the lightest nonet of the MIT-bag [9], in the $\gamma\gamma$-collisions should be suppressed by the value order in comparison with the $a_0(980)$-meson

taken as the two-quark P-wave state. In the four-quark model there was obtained the estimate [8]

$$\Gamma(a_0(980) \to \gamma\gamma) \sim 0.27\,\mathrm{keV}, \tag{10}$$

which was confirmed by experiment [10,11]

$$\begin{aligned}&\Gamma(a_0 \to \gamma\gamma) = (0.19 \pm 0.07^{+0.1}_{-0.07})/B(a_0 \to \pi\eta)\,\mathrm{keV}, \text{ Crystal Ball},\\ &\Gamma(a_0 \to \gamma\gamma) = (0.28 \pm 0.04 \pm 0.1)/B(a_0 \to \pi\eta)\,\mathrm{keV}, \text{ JADE}.\end{aligned} \tag{11}$$

At the same time in the two-quark model (8) it was anticipated [12,13] that

$$\Gamma(a_0 \to \gamma\gamma) = (1.5 - 5.9)\Gamma(a_2 \to \gamma\gamma) = (1.5 - 5.9)(1.04 \pm 0.09)\,\mathrm{keV}. \tag{12}$$

The wide scatter of the predictions is connected with different reasonable guesses of the potential form.

2.2. Evidences for strange quarks in the $f_0(980)$-meson

As for the $\phi \to \gamma f_0(980) \to \gamma\pi^0\pi^0$-decay, the more sophisticated analysis is required.

The structure of the $f_0(980)$-meson, from which the $\pi^0\pi^0$-system originates, in general, is

$$Y = f_0(980) = \tilde{c}_0 gg + \tilde{c}_1(u\bar{u} + d\bar{d})/\sqrt{2} + \tilde{c}_2 s\bar{s} + \tilde{c}_3 s\bar{s}(u\bar{u} + d\bar{d})/\sqrt{2} + \ldots\,. \tag{13}$$

First we discuss a possibility to treat the $f_0(980)$-meson as the quark-antiquark state.

The hypothesis that the $f_0(980)$-meson is the lowest two-quark P-wave scalar state with the quark structure

$$f_0 = (u\bar{u} + d\bar{d})/\sqrt{2} \tag{14}$$

contradicts Eq. (1) in view of OZI, much as Eq. (8) contradicts Eq. (2) (see the above arguments).

Besides, this hypothesis contradicts a variety of facts:

i) the strong coupling with the $K\bar{K}$-channel [14,5]

$$1 < R = |g_{f_0K^+K^-}/g_{f_0\pi^+\pi^-}|^2 \leq 8\,, \tag{15}$$

for from Eq. (14) it follows that $|g_{f_0K^+K^-}/g_{f_0\pi^+\pi^-}|^2 = \lambda/4 \simeq 1/8$, where λ takes into account the strange sea suppression;

ii) the weak coupling with gluons [15]

$$B(J/\psi \to \gamma f_0(980) \to \gamma\pi\pi) < 1.4 \cdot 10^{-5} \tag{16}$$

opposite the expected one [16] for Eq. (14)

$$B(J/\psi \to \gamma f_0(980)) \geq B(J/\psi \to \gamma f_2(1270))/4 \simeq 3.4 \cdot 10^{-4}\,; \tag{17}$$

iii) the weak coupling with photons [18,19]

$$\begin{aligned}&\Gamma(f_0 \to \gamma\gamma) = (0.31 \pm 0.14 \pm 0.09)\,\mathrm{keV}, \text{ Crystal Ball},\\ &\Gamma(f_0 \to \gamma\gamma) = (0.24 \pm 0.06 \pm 0.15)\,\mathrm{keV}, \text{ MARK II}\end{aligned} \tag{18}$$

opposite the expected one [12,13] for Eq. (14)

$$\Gamma(f_0 \to \gamma\gamma) = (1.7 - 5.5)\Gamma(f_2 \to \gamma\gamma) = (1.7 - 5.5)(2.8 \pm 0.4)\,\text{keV}; \tag{19}$$

iv) the decays $J/\psi \to f_0\omega$, $J/\psi \to f_0\phi$, $J/\psi \to f_2\omega$, $J/\psi \to f_2'\phi$ [6]

$$B(J/\psi \to f_0(980)\omega) = (1.4 \pm 0.5) \cdot 10^{-4}\,. \tag{20}$$

$$B(J/\psi \to f_0(980)\phi) = (3.2 \pm 0.9) \cdot 10^{-4}\,. \tag{21}$$

$$B(J/\psi \to f_2(1270)\omega) = (4.3 \pm 0.6) \cdot 10^{-3}\,, \tag{22}$$

$$B(J/\psi \to f_2'(1525)\phi) = (8 \pm 4) \cdot 10^{-4}\,, \tag{23}$$

The suppression

$$B(J/\psi \to f_0(980)\omega)/B(J/\psi \to f_2(1270)\omega) = 0.033 \pm 0.013 \tag{24}$$

looks strange in the model under consideration as well as Eq. (7) in the model (8).

The existence of the $J/\psi \to f_0(980)\phi$-decay of greater intensity than the $J/\psi \to f_0(980)\omega$-decay (compare Eq. (20) and Eq. (21)) shuts down the model (14) for in the case under discussion the $J/\psi \to f_0(980)\phi$-decay should be suppressed in comparison with the $J/\psi \to f_0(980)\omega$-decay by the OZI-rule.

So, Eq. (14) is excluded at a level of physical rigor.

It is impossible to consider the $f_0(980)$-meson as the near $s\bar{s}$-state without a gluon component [17].

The introduction of a gluon component, gg, in the $f_0(980)$-meson structure allows the weak coupling with gluons (16) to be resolved easy. Really, by [16],

$$\begin{aligned} &B(R[q\bar{q}] \to gg) \simeq O(\alpha_s^2) \simeq 0.1 - 0.2\,, \\ &B(R[gg] \to gg) \simeq O(1)\,, \end{aligned} \tag{25}$$

then the minor ($\sin^2\alpha \le 0.08$) dopant of the gluonium

$$\begin{aligned} &f_0 = gg\sin\alpha + \left[\left(1/\sqrt{2}\right)(u\bar{u} + d\bar{d})\sin\beta + s\bar{s}\cos\beta\right]\cos\alpha\,, \\ &\tan\alpha = -O(\alpha_s)\left(\sqrt{2}\sin\beta + \cos\beta\right)\,, \end{aligned} \tag{26}$$

allows to satisfy Eqs. (15), (16) and to get the weak coupling with photons

$$\Gamma(f_0(980)) \to \gamma\gamma) < 0.22\,\text{keV} \tag{27}$$

at

$$-0.22 > \tan\beta > -0.52\,. \tag{28}$$

So, $\cos^2\beta > 0.8$ and the $f_0(980)$-meson is near the $s\bar{s}$-state, as in [20].

The scenario, in which with Eq. (26) the $a_0(980)$-meson is the two-quark state (8), runs into following difficulties:

i) it is impossible to explain the f_0 and a_0-meson mass degeneration;
ii) it is possible to get only [4,5]

$$B(\phi \to \gamma f_0 \to \gamma\pi^0\pi^0) \simeq 1.7 \cdot 10^{-5}\,, \qquad B(\phi \to \gamma a_0 \to \gamma\pi^0\eta^0) \simeq 10^{-5}\,; \tag{29}$$

iii) it is predicted

$$\Gamma(f_0 \to \gamma\gamma) < 0.13 \cdot \Gamma(a_0 \to \gamma\gamma)\,, \tag{30}$$

that is on the verge of conflict with the experiment, compare Eqs. (11) and (18);
iv) it is also predicted

$$B(J/\psi \to a_0(980)\rho) = (3/\lambda \approx 6) \cdot B(J/\psi \to f_0(980)\phi)\,, \tag{31}$$

that has almost no chance, compare Eqs. (6) and (21).

Note that the λ independent prediction

$$B(J/\psi \to f_0\phi)/B(J/\psi \to f_2'\phi) = B(J/\psi \to a_0)\rho)/B(J/\psi \to a_2\rho) \tag{32}$$

is excluded by the central figure in

$$B(J/\psi \to f_0(980)\phi)/B(J/\psi \to f_2'(1525)\phi) = 0.4 \pm 0.23\,, \tag{33}$$

obtained from Eqs. (21) and (23), compare with Eq. (7). But, certainly, experimental error is too large. Even twofold increase in accuracy of measurement of Eq. (33) could be crucial in the fate of the scenario under discussion.

The prospects to consider the $f_0(980)$-meson as the near $s\bar{s}$-state (26) and the $a_0(980)$-meson as the four-quark state (9) with the coincidental mass degeneration is rather gloomy especially as the four-quark model with the symbolic structure

$$f_0 = s\bar{s}(u\bar{u} + d\bar{d})\cos\theta/\sqrt{2} + u\bar{u}d\bar{d}\sin\theta\,, \tag{34}$$

built around the MIT-bag [9], justifies all unusual features of the $f_0(980)$-meson [14,21,17].

As for the molecular model, wherein the $a_0(980)$ and $f_0(980)$-mesons are the extended bound states of the $K\bar{K}$-system [22], it seems that the experiment leave no chance to this model now [17].

As for the traditional question, where are the scalar two-quark states from the lowest P-wave multiplet with the quark structures (8) and (14), there is no a tragedy with it now. All members of this multiplet are established [6,17].

3. The theoretical grounds for the four-quark model

A few words on the theoretical grounds for the four-quark nature of the f_0 and a_0 mesons. It was shown in the context of the MIT-bag [9] that the low-lying scalar four-quark nonet as bound state of diquarks ($T_a = \varepsilon_{abc}\bar{q}^b\bar{q}^c$ and $\bar{T}^a = \varepsilon^{abc}q_bq_c$, note that similar diquarks binding up with quarks to form the baryon octet) arises from the strong binding energy in such a configuration due to a hyperfine interaction Hamiltonian of the form

$$H_{hf} = -\Delta \sum \vec{s}_i \cdot \vec{s}_j \vec{F}_i \cdot \vec{F}_j\,, \quad \vec{s} = \vec{\sigma}/2\,, \;\; \vec{F} = \vec{\lambda}/2\,.$$

In the last few years the true renaissance has been going in treatments of $\pi\pi$ and πK scattering with help of phenomenological linear σ models, see, for example, [23–27]. It has been argued on occasion that the corresponding scalar mesons are quark-antiquark states. But in fact at the Lagrangian level there is no difference in the formulation of the two-quark and four-quark cases [28].

4. Conclusion

So, there are many reasons to consider the $a_0(980)$ and $f_0(980)$ mesons as the four-quark states. Nevertheless, in summary one emphasizes once again that the further study of the decays $\phi \to \gamma f_0$ and $\phi \to \gamma a_0$; $J/\psi \to a_0\rho$, $f_0\omega$, $f_0\phi$, $a_2\rho$, $f_2\omega$, and $f_2'\phi$; $a_0 \to \gamma\gamma$ and $f_0 \to \gamma\gamma$; $D_s \to f_0\pi$ and $D_s \to a_0\pi$ [29] will enable one to solve the question on the $a_0(980)$ and $f_0(980)$-meson nature, at any case to close the above scenarios.

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